THERMAL IMPROVEMENT OF VISION CONTROL WINDOWS

RENEWABLE ENERGY BRANCH

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PREFACE

This is the final report containing the theoretical and experimental studies on the Vision Control windows carried out during 1986 - 1987. It presents the theoretical and experimental research methodologies and findings in a condensed format. The scope of work was the theoretical study and experimental verification of the possible improvements of the thermal and optical characteristics of the Vision Control windows.

Vision Control windows are automated venetian blind window systems containing horizontal pivoted louvers installed and sealed between the two glass panes. In addition to the thermal characteristics of the ordinary insulating windows, they have excellent shading coefficients which make them suitable for use in solariums, green houses and high rise buildings. Within the Super Window Program of Energy, Mines and Resources, the thermal improvement of these systems is desirable and essential so that in addition to their good optical characteristics their thermal resistance can be economically improved. Since there was not an appropriate design tool to make these improvements, this research has been carried out.

It is hoped that the methodology and the findings of this study will be useful to the experts and designers in the Super Window field.

ABSTRACT

The objectives of this project were to study the heat transfer through a Vision Control window system and to develop a design tool for improvement, modification and better utilization of materials.

The heat transfer by convection, conduction and radiation through the window system is studied theoretically and its thermal performance is determined. The solution of the governing equations (system of non-linear equations) is carried out by using an iterative numerical method. As a result, a thermal model has been developed to use as a design tool in the study of improvements of the Vision Control windows. A theoretical study has been carried out to identify the possible improvement areas and then an experimental study is carried out using a variable temperature calorimeter to verify the theoretical results and the suggested improvements. It has been found that the Vision Control window system can be improved by using low ϵ coating at the inside surface of the inside glass and heat absorbing glass as the inside glass pane depending on the requirements.

A system study is carried out for a single one-zone building using typical summer and winter days and the optimum strategy is determined to minimize the auxiliary energy requirements by modulating the louver position at an optimum angle. The thermal performance of the system is compared to that of a similar system without the louvers and it is found that considerable energy economy in summer and winter is possible by an automatic control of the louver positions.

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EXECUTIVE SUMMARY

Vision Control windows are venetian blind window systems incorporating horizontal pivoted louvers installed and sealed between two glass panes. They have excellent shading coefficients with thermal resistance characteristics equal to or slightly higher than those of double insulating windows. The main objectives of this project were to study the thermal performance and identify the possible improvement areas and develop an optimum louver control strategy.

The heat transfer by convection, conduction and radiation through the window system is studied theoretically; the assumptions for the solution of the problem were: 1. heat transfer is one dimensional; 2. heat exchanges are at steady state for the whole system; 3. heat transfer by convection is negligible over the louvers; 4. materials used are diffuse gray surfaces. The solution of the resulting system of non linear equations is carried out by using an iterative numerical method.

Using the thermal model as a design tool, a parametric study was carried out; the parameters identified for thermal improvement of the system were: 1. emittance of the glass; 2. absorptance of the glass; 3. emittance of the louver surfaces; 4. distance between the glass surface and the louver ends. The results of the parametric study indicated that the parameters 1 and 2 could result in the thermal and optical improvement of the system.

Based on these results, an experimental study using three prototype windows was carried out; the first window was an ordinary Vision Control window with 6 mm clear glass panes and it was taken as a reference system; the second was an identical window to the first with low emittance coating applied at the inner

surface of the inside glass pane; finally, the third was an identical window to the first with heat absorbing glass at the inside pane. A variable temperature calorimeter was used in the experimental studies; it is a 0.61 m by 0.67 m by 0.64 m high box, fabricated from plywood and styrofoam; it has an opening of 0.30 m by 0.47 m to install the prototype windows. The test apparatus is instrumented to measure the total solar radiation on the horizontal surface and the beam component of the solar radiation, the air temperatures and the glass temperatures; a data acquisition system is used to collect, record and compile the data. The experimental studies were carried out for several days using the three windows described above.

The theoretical results obtained by using the thermal model are compared to those experimental using various parameters such as floating box temperature, glass temperatures, etc. and using the experimental results, the thermal resistance and the shading coefficient of the systems are calculated.

The results indicated that

1. the accuracy of the thermal model developed was satisfactory and it could be used as a design tool to predict the thermal performance of these systems and to identify the improvement areas;

2. using low emittance coating on the inside surface of the inside glass pane, the thermal resistance of the system could be improved by 58 to 73 % with respect to the reference system;

3. using heat absorbing glass at the inside pane, the shading coefficient of the system could be improved by 60 % with respect to the base system;

4. by keeping the louver angles at optimum values, a considerable energy economy was possible in winter and summer climatic conditions.

It is concluded that

1. the thermal and optical characteristics of the Vision Control windows can be improved by incorporating the low emittance glass and/or heat absorbing glass in the present design and manufacture;

2. in order to implement a wide use of the improved systems, a simplified design tool for users should be developed based on the results of this study;

3. in order to implement the optimum strategy for louver angles and to promote an energy economy, an automatic control device should be developed.

1. INTRODUCTION

The window has been a source of particular concern to energy researchers because of its potentially large heat gains and losses. As a result, many designers have explored ways of minimizing the thermal losses of windows while preserving their lighting and psychological benefits. Among the techniques suggested for improving window performance, the use of shading devices, both internal and external can be mentioned.

The use of various types of shading devices as blinds for building thermal control and for solar assisted heating, cooling and lighting has been subject to various architectural [1], theoretical [2] and experimental [3] studies. Venetian blinds are a particularly versatile shading device, allowing selective control over a window characteristic by means of adjusting the angle of the louvers. Despite continuous use of blinds and many studies, heat transfer through a window with blinds is not satisfactorily formulated and solved; empirical formulas existing in the literature [4,5] are not sufficient to calculate the dynamic behavior of sophisticated blind systems; in particular a system with blinds installed between two glazing panes is not yet studied.

Vision Control system manufactured and marketed by Unicel Inc. with a double glazed unit incorporates pivoting louvers hermetically sealed between two glass panes. This system has found applications particularly in solariums, green houses, high rise buildings and design offices. In this study, the thermal behavior of the system with internal louvers coupled with a typical room is studied in terms of thermal gains, auxiliary heating of the room and temperature fluctuations of the room air. In particular, the heat transfer is computed through the window and in the room in terms of solar radiation, infra-red radia-

tion, convection and conduction.

2. OBJECTIVES

The main objectives of this project were:

1. Improvement of thermal and optical characteristics of Vision Control windows fabricated by Unicel;

2. Thermal analysis (by radiation, convection and conduction) of the system to develop a design tool for improvement, modification and better utilization of materials.

3. THEORETICAL ANALYSIS

The system studied is shown in Fig. 1. The two tempered glass panes with a thickness e are set apart at a distance D ; the distance from the edges of the louvers to the surface of the glass panes is d_o for the outside glass and d_i for the inside glass respectively; the louvers are fixed at both ends to the side of the window and can rotate around the z axis; the fully open position corresponds to $\beta = 0$ from the xz plane; they can rotate by means of a mechanical system outside the window seal clockwise to - 90^o or anti-clockwise to + 90^o from that plane. The louvers are made of aluminium coated with a white paint; their width L is the same as the distance separating them in the y direction.

The theoretical analysis has been carried out to determine the net heat exchange by radiation and convection, and to obtain the thermal performance of the system. Due to symmetry, the domain of study is represented by a fictive

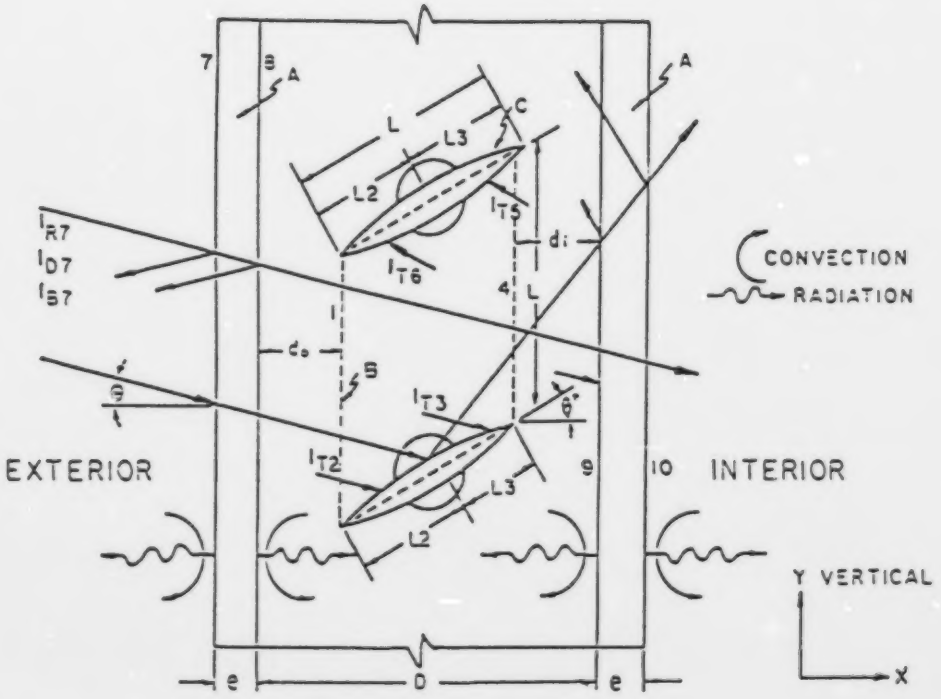


Figure 1. Schematic of an automated venetian blind window system.

boundary shown in Fig. 2. where all the elements are L_k long and w wide in the z direction. For convenience w can be taken as 1 m. All the heat exchanges in the window system are analyzed within this domain except those of natural and forced convection which require the full size.

At the boundary outside the external glass, the solar radiation is received with a known outside temperature and a wind velocity. The room temperature is calculated in an iterative manner as a function of the temperature of the preceding time period and forced to stay within the range of a comfort zone by auxiliary heating or ventilating depending on the case.

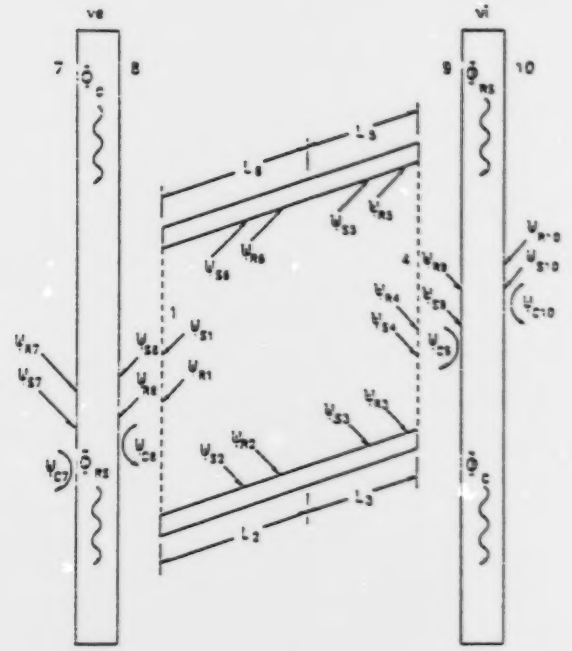


Figure 2. Schematic of a cell with radiation and convection heat fluxes written for the elements.

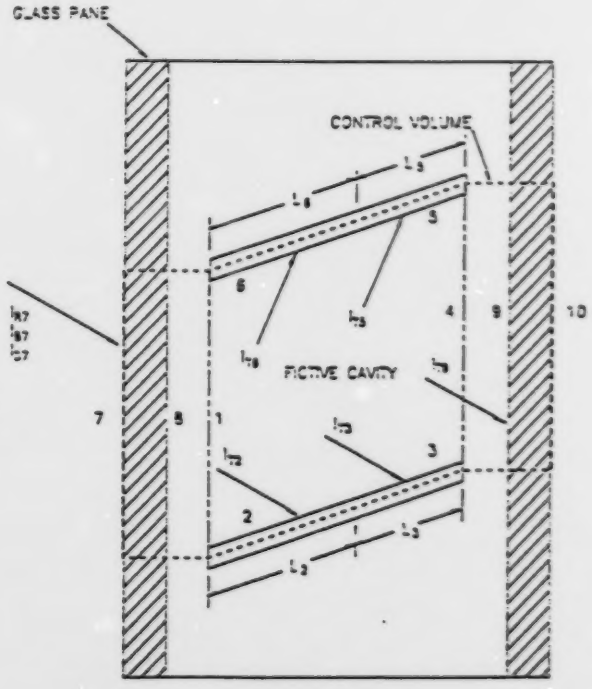


Figure 3. Sub-system components with respective incident solar radiation.

The analysis has been carried out with the following assumptions:

o Heat transfer is uni-dimensional, the only temperature gradient is in the x direction.

o Heat exchanges are at steady state for the whole system at the time interval considered except for the room temperature which is time dependent.

o Material properties are independent of temperature, at the temperature level of interest; or their average values can be calculated at a given temperature level.

o Each element of the sub-system is considered isothermal. This assumption has been validated by an experimental study carried out in our laboratory.

o The room air temperature is maintained within the range of the comfort zone from 18.3°C to 24.6°C.

o Good insulation is provided for the window mounting so that the lateral heat losses can be neglected.

o All the elements are considered diffuse gray surfaces.

o The radiative heat exchanges with the room walls are considered as if all the surfaces are blackbodies at inside air temperature.

o The heat exchange on the louvers is assumed to be by I.R. and solar radiation only. The problem regarding the natural convection in the window cavity

with louvers is a complex one due to the fact that the louvers do not touch either one of the glass panes, and the effect of the convection flow will be different for different position angles β with respect to the xz plane; these different flow regimes may result in different temperature gradients between the two glass panes. There is evidence [6] that with Rayleigh number in the range from 10^3 to 10^5 a high temperature gradient near the walls and uniform temperature gradient in the vertical direction will be present; that means a boundary layer flow regime will be present. There is also experimental evidence [7,8] indicating that the assumption of two-dimensional flow in the case of a long cavity in the normal direction is valid, provided the Rayleigh number based on cavity height is less than 10^8. In this study, the Rayleigh number will go from 10^3 for a temperature gradient of 0.1^oC between the glasses to 10^5 for the highest temperature gradient in the system. It can be concluded that near the glass panes a boundary layer flow regime will be present. It is also known that for surfaces with high emittance, the net convective energy absorbed is negligible compared to that by radiative exchange.

With these assumptions, total radiative exchange can be divided into solar and I.R. radiation and analyzed separately. Fig. 2. shows all the components of heat exchange for the system in terms of solar radiative exchange (ψ_{kS}), I.R. radiative exchange (ψ_{kR}), convective exchange (ψ_{kC}), net convective energy absorbed (Φ_{kC}) and net radiative energy absorbed (Φ_{kRS}). Note that the louvers have been divided into two length zones, one for the three components of radiation and the other for diffuse and reflected components only.

3.1. SOLAR RADIATIVE EXCHANGE

Solar radiation consists of diffuse, direct and reflected components. The

transmission of these components in the window can be calculated using the relations used in the literature [9] considering the absorption for both panes of glass. For certain incidence angle of the sun on the window, some parts of the system receive direct radiation and others do not. In order to make the solar radiation heat balance on all surfaces, the incident solar radiation flux on each surface is determined. Fig. 3 shows the different elements considered in the sub-system for the analytic resolution of solar radiation with their respective solar irradiance.

On elements 2 and 6, are all three components of the solar radiation while on 3 and 5 are those by diffuse and reflected radiation. On element 9, all three components of the solar radiation may be received coming from the outside glass. During a certain period, the length of some elements L_2, L_6, L_3 or L_5 can be zero depending on the incidence angle of the sun on the glass.

For a two dimensional domain, the porosity of the system is defined as:

$$F_b = [1 - (\sin(\beta + \Theta) / \cos\Theta)]^* \qquad (1)$$

with $[x]^* = (|x| + x)/2$ where x is the expression in the brackets.

For the incident solar radiation on the surfaces:

$$I_{T2} = L_2 \, w \, ((1 - F_b) \, \tau_b \, I_b + F_{2GR} \, \tau_r \, I_r + F_{2SKY} \, \tau_d \, I_d) \qquad (2)$$

$$I_{T3} = (L - L_2) \, w \, (F_{3GR} \, \tau_r \, I_r + F_{3SKY} \, \tau_d \, I_d) \qquad (3)$$

$$I_{T6} = L_6 \, w \, ((1 - F_b) \, \tau_b \, I_b + F_{6GR} \, \tau_r \, I_r + F_{6SKY} \, \tau_d \, I_d) \qquad (4)$$

$$I_{T5} = (L - L_6)\, w\, (F_{5GR}\, \tau_r\, I_r + F_{5SKY}\, \tau_d\, I_d) \qquad (5)$$

and finally for I_{T9}, the reflections in the fictive cavity are diffuse so that its three components can be written as:

$$I_{9b} = \tau_b\, I_b\, L\, w - (1 - F_b)\, (\tau_b\, I_b\, L_2\, w + \tau_b\, I_b\, L_6\, w) \qquad (6)$$

$$I_{9d} = \tau_d\, I_d\, L\, w - w\, (F_{2SKY}\, \tau_d\, I_d\, L_2 + F_{6SKY}\, \tau_d\, I_d\, L_6 + F_{3SKY}\, \tau_d\, I_d\, (L - L_2) + F_{5SKY}\, \tau_d\, I_d\, (L - L_6)) \qquad (7)$$

$$I_{9r} = \tau_r\, I_r\, L\, w - w\, (F_{2GR}\, \tau_r\, I_r\, L_2 + F_{6GR}\, \tau_r\, I_r\, L_6 + F_{3GR}\, \tau_r\, I_r\, (L - L_2) + F_{5GR}\, \tau_r\, I_r\, (L - L_6)) \qquad (8)$$

In order to resolve the solar radiative exchange, the fictive cavity is taken as the domain of computation; then the solar radiosity for each surface is written as:

$$R_{kS} = (1 - \epsilon_k)\, \left(\sum_{j=1}^{6} F_{kj}\, R_{jS} + (I_{kT}/(L_k\, w)) \right) \qquad (9)$$

where k represents the surface element in Fig. 2: the solar irradiance can be written as:

$$E_{kS} = \sum_{j=1}^{6} F_{kj}\, R_{jS} \qquad (10)$$

The net solar radiation absorbed by each surface can be calculated by using the net radiation method [10,11].

Knowing the equations for radiosity, solar irradiance, and incident solar radiation for all the surfaces it is possible to obtain a system of simultaneous equations and find the components R_k and E_k for all the elements, leading to the following equation describing the net solar radiation absorbed by each surface:

$$\Phi_{kS} = R_{kS} - E_{kS} \qquad (11)$$

3.2. I.R. RADIATIVE EXCHANGE

As in the case of solar radiative exchange, the I.R. radiative exchange in the fictive cavity is solved using the net radiation method.

Following the assumptions discussed earlier for gray-diffuse surfaces, the I.R. radiosity of all surfaces is:

$$R_{kR} = \epsilon_k \sigma T_k + (1 - \epsilon_k) \sum_{j=1}^{6} F_{kj} R_{jR} \qquad (12)$$

The I.R. irradiance is written as:

$$E_{kR} = \sum_{j=1}^{6} F_{kj} R_{jR} \qquad (13)$$

for example for the surface 1:

$$R_{1R} = \epsilon_1 \sigma T_1^4 + (1 - \epsilon_1) [F_{12} (\epsilon_2 \sigma T_2^4 + (1 - \epsilon_2) R_{2R}) + F_{13} (\epsilon_3 \sigma T_3^4 + (1 - \epsilon_3) R_{3R}) + F_{14} (\epsilon_4 \sigma T_4^4 + (1 - \epsilon_4) R_{4R}) + F_{15} (\epsilon_5 \sigma T_5^4 + (1 - \epsilon_5) R_{5R}) + F_{16} (\epsilon_6 \sigma T_6^4 + (1 - \epsilon_6) R_{6R})] \quad (14)$$

Similar equations can be written for the other surfaces. Eq. 13 specified for all surfaces of the fictive cavity will result in a system of simultaneous equations which cannot be solved explicitly since all the surface temperatures are not known.

The I.R. radiation absorbed by all the surfaces can be expressed in the same way as for solar radiation:

$$\Phi_{kR} = R_{kR} - E_{kR} \quad (15)$$

3.4. TOTAL RADIATIVE EXCHANGE

The total radiation exchanged for each surface is obtained by summing solar and I.R. radiations:

$$\Phi_{kRS} = \Phi_{kR} + \Phi_{kS} \quad (16)$$

ENERGY BALANCE

Energy balance can be analyzed for the whole window by transferring the net total radiative exchange on surfaces 1 and 4 of the fictive cavity to the outside glass and inside glass respectively.

The net total radiation absorbed by the outside glass is:

$$\Phi_{oRS} = \Phi_{1RS} + (\epsilon_0 \sigma T_0^4 - \epsilon_0 F_{0SKY} \sigma (T_{SKY}^4 + T_{GR}^4)) \qquad (17)$$

with $T_{GR} = T_a$ and $T_{SKY} = T_{GR} (0.8 + T_{dp}/250))^{0.25}$

by the inside glass:

$$\Phi_{iRS} = \Phi_{4RS} + (1/\epsilon_i + 1/\epsilon_m - 1) \sigma (T_i^4 - T_e^4) \qquad (18)$$

and by the louver:

$$\Phi_{LRS} = \Phi_{2RS} + \Phi_{3RS} + \Phi_{5RS} + \Phi_{6RS} \qquad (19)$$

Energy Balance Equations:

1) for the outside glass:

$$\psi_{c7} + \psi_{c8} + \Phi_{oRS} = 0 \qquad (20)$$

In order to compute the external convection on the outside glass, the correlation of McAdams [12] for natural convection is coupled with the correlation of

Sparrow et al. [13] for forced convection on a plate with finite dimensions.

For laminar regime: $10^4 < Gr < 10^9$

$$Nu = [0.59\ (Gr\ Pr)^{0.25},\ 0.86\ Re^{0.5}\ Pr^{0.33}]_{max} \qquad (21)$$

For turbulent regime: $Gr > 10^9$

$$Nu = [0.13\ (Gr\ Pr)^{0.33},\ 0.86\ Re^{0.5}\ Pr^{0.33}]_{max} \qquad (22)$$

In both Eqs. 21 and 22, Reynolds number is defined as:

$$Re = V\ \ell\ /\ \nu \qquad (23)$$

where the characteristic length is:

$$\ell = 2\ HW/(H + W) \qquad (24)$$

Since the distance from the end of a louver to the glass is large, and the louver's emittance is high, it is possible to neglect the louvers for the convection phenomena in the cavity for all situations except when they are at an angle of -90^o or $+ 90^o$ in which case the system will consist of two long cavities. So the correlation for the Nusselt number can be written for Ra between 10^3 and 10^5 as [14]:

$$Nu = 0.138\ Ra^{0.30} \qquad (25)$$

This equation has been found to fit well that of Hollands et al. [15] which

is a more complex equation.

2) For the louvers:

$$\Phi_{LC} + \Phi_{LRS} = 0 \qquad (26)$$

And since Φ_{LC} can be neglected, Eq. 26 can be written in the form:

$$\Phi_{LRS} = 0 \qquad (27)$$

3) For the inside glass:

$$\Psi_{9C} + \Psi_{10C} + \Phi_{iRS} = 0 \qquad (28)$$

The Nusselt number in Eq. 25 is used for the solution of Ψ_{8C} as well as for Ψ_{9C}. The McAdams correlation [12] is used to determine the convection coefficient for Ψ_{10C}.

Since the assumption is made that room temperature can vary within a comfort zone, it is necessary to define the governing equations to evaluate the room temperature and the auxiliary heating, if necessary, to maintain the calculated T_e within the range from 18.3°C to 24.6°C.

For the room temperature T_e:

$$T_e^{i+1} = T_e^{i} + \Delta t \,/\, \rho C_p Vol \,(Q_T + Q_{con} + Q_S) \qquad (29)$$

where Q_T defines the global heat exchange by convection and radiation with

room air as:

$$Q_T = A\,[h_{iC}\,(T_i - T_e) + \epsilon_i\,\epsilon_m\,\sigma\,(T_i^4 - T_e^4)] \qquad (30)$$

and Q_{con} represents the heat losses by conduction of the walls as:

$$Q_{con} = UA\,(T_a - T_e) \qquad (31)$$

and finally Q_S represents the solar radiation flux absorbed which is incident on the inside surfaces; this can be estimated as an overall input to the air in the room involving an overall absorption coefficient α_g including the effects of incident fluxes from the window as well as multiple reflections from all surfaces within the room.

$$Q_S = \alpha_g\,(\tau_d\,E_{4S}\,L_4\,w + \tau_b\,I_{gb} + \tau_d\,I_{gd} + \tau_r\,I_{gr}) \qquad (32)$$

For the auxiliary heat:

$$Q_{aux} = \rho\,C_p\,Vol\,(T_{lim} - T_e)\,/\,\Delta t \qquad (33)$$

where T_{lim} equal to 18.3 or 24.6 C depending of the value of T_e.

4. SOLUTION TECHNIQUE

In order to solve the equations defining the whole system (Eqs. 20,26 and 28), a numerical iterative technique is used since for the I.R. radiative exchange in the fictive cell and for the convective exchange, the temperatures of the elements of the system must be known.

Since several non-linear simultaneous equation systems exist, a simple iterative procedure will not be sufficient. The solution procedure followed is given below:

1) For an instant t, the solar radiation fluxes incident on the surfaces, and the length which is subject to obtain a linear system by the net radiation method in the fictive cavity are computed as a result of which all the Φ_{kS} are determined.

2) The room air temperature and the auxiliary heat are then computed except at the first step.

3) All the unknown temperatures are initialized T_o^t, T_L^t, T_i^t to values which may be T_o^{t-1}, T_L^{t-1}, T_i^{t-1} for all time except the first step.

4) The non-linear system obtained by the net radiation method for the I.R. radiative exchange which is now linearized is solved by inserting the unknown temperatures. Hence Φ_{kR} can be obtained for all the surfaces of the fictive cavity.

5) The convective heat exchange on all surfaces of the whole system is solved which leads to Φ_{kC}.

6) The energy balance equations on all surfaces are solved. If the balances are not satisfied, new temperatures T_o^t, T_L^t and T_i^t are computed and returned to step 4. If the balances are satisfied, the computation returns to step 1 for the next period.

Multiple iterative processes have been tried to solve the energy balance equations; however since the system is very sensitive to fluctuations of the unknown temperatures, the iterative method chosen is the half interval method [16]; it has been found that this method is not well suited to obtain the convergence of T_L, T_o and T_i at the same time; therefore an iterative process has been used that will solve the temperatures separately one after another until all three satisfy the energy balance equation.

5. STUDY OF VARIOUS SYSTEM PARAMETERS

In order to determine the improvement points of the Vision Control windows and to provide the necessary information for the automatic control of the louvers, various system parameters, namely the system thermal resistance, shading coefficient and optimum louver angles are studied.

System Thermal Resistance:

The system thermal resistance is calculated as:

$$R_T = R_o + R_{L-o} + R_{L-i} + R_i \qquad (34)$$

where $R_j = 1/(h_{Rj} + h_{cj})$ with $j = o$ or i.

Shading Coefficient:

Following [17], the shading coefficient and the net gain are:

$$SC = SHGF_{ven}/SHGF_{DSA} \quad (35)$$

$$q_{net} = (SC)\ (SHGF_{DSA}) + U_{top}\ (T_a - T_e) \quad (36)$$

Thermal Resistance of the System and Parametric Study:

In order to identify the components of the window which could cause a thermal improvement of the system, a theoretical study was carried out for $\beta = 0$ deg. First of all, the thermal resistance of the system without and with louvers was calculated and a reference base was established ; it was found that for the winter the thermal resistance of the system with louver was 13 % higher than the one without it and that the shading coefficient was lower by about 29 %; the corresponding figures for the summer were 21% and 25% respectively. These values can be compared to those experimentally obtained by National Testing Laboratories, York, PE. which are given in the catalogue of Vision Control : the average thermal resistance is 0.35 m^2C/W for winter and 0.37 m^2C/W for summer; the average shading coefficient is 0.53. It can be seen that the thermal model developed predicts the thermal performance and the optical characteristics of the Vision Control system with an acceptable accuracy. The thermal resistances of the same window without louvers taken from [17] are about 0.28 m^2C/W (summer) - 0.30 m^2C/W (winter) which are also in good agreement with the theoretical results.

A parametric study was carried out to see the effects of various parameters on the thermal resistance of the system with louvers; the parameters were: the glass surface emissivity and heat absorbing characteristics of the glass, the emissivity of louver surface, distance d_i and d_o. The results are presented in Table 1. It can be seen that among the various possible improvements, the use of a glass with low emissivity applied on the surface 9 of Fig. 1 is the best

with 77 % increase in system thermal resistance and that the heat absorbing glass improves considerably the shading coefficient of the system, although its thermal resistance remains the same. It is seen that the low emittance coating of the louver surfaces and the decreasing of the distance from the glass surface to the louver ends will not improve the thermal characteristics of the system. Therefore, based on these results it was decided that an experimental study be carried out with prototype windows incorporating i) low emittance coating on the surface 9 of Figure 1 and ii) heat absorbing glass used as glass pane 9 of Figure 1.

Optimum Louver Angle:

In order to determine if an automatic control of the louvers would help reduce the energy waste and in the affirmative to provide the necessary information for the automatic control of the louvers, a theoretical study was carried out for a typical summer (air conditioning may be required) and winter (heating may be required) day . The optimum louver angles are those for which the floating room temperature is at the comfort zone limits from 18.3° to 24.5 °C or closest to the zone limits; the optimum temperatures are the upper limit in the summer and the lower limit in the winter. The auxiliary energy for cooling or heating is calculated as the energy required to make the room temperature equal to the upper limit of 24.5°C in the summer and to the limit of 18.3°C in the winter from the floating room temperature corresponding to the optimum louver angle. If the floating room temperature is in the comfort zone, there is no need for an auxiliary energy for cooling in the summer or heating in the winter. This optimization study was carried out for the case of a single one-zone building (single indicates a detached building) in London, Ontario (Latitude 43.3°, Altitude 200 m.). Its dimensions were 1.2 x 2.5 x 3.5 m with 1.15 x 2.25 window

area; its thermal characteristics were (UA) = 6.0 W/K excluding the window. A typical day during both cooling and heating seasons was taken for the simulation. The days considered were February 18 and July 21; the climatic conditions (T_a and I_T) used as reference for the optimization of the louver angle are shown in Figs. 4 and 5 for summer and winter periods respectively.

Table 1. Effects of various parameters on the system thermal resistance.

		BASE SYS. WITHOUT LOUVER	BASE SYS. WITH LOUVER	LOW-ϵ GLASS	LOW-ϵ LOUVER	HEAT ABS. GLASS	D 40 mm
THERMAL RESIST.	S	0.29	0.35	0.59	0.34	0.34	0.35
	W	0.30	0.34	0.46	0.34	0.34	0.34
SHADING COEFF.	S	0.75	0.56	0.56	0.56	0.26	0.56
	W	0.76	0.54	0.54	0.54	0.24	0.54

S = Summer; W = Winter; Thermal Resistance is expressed in m^2C/W

Auxiliary Energy:

The floating room temperature and the auxiliary energy of an identical single one-zone building with an ordinary double glass window having the same optical characteristics as the automated venetian blind system are also calculated using the same methodology and the results are used as a reference. These results are shown in Figs 4 and 5. Then a performance factor has been defined as:

$$PF = (Q_{aux\ reg} - Q_{aux\ ven}) / Q_{aux\ reg} \qquad (37)$$

using Eq. 33 and outside the comfort zone, i.e. $T_{e\ reg} < 18.3^oC$ and $T_{e\ reg} > 24.5^oC$, PF can be written as a function of temperature:

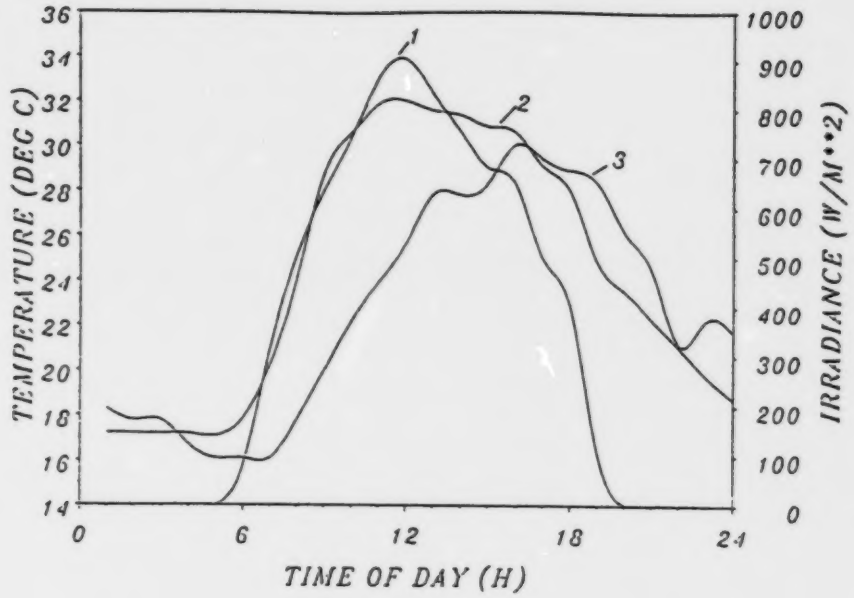


Figure 4. Reference conditions for summer. 1. Irradiance, 2. Floating room temperature of the single one zone cell with an ordinary double glass window, 3.Outside air temperature.

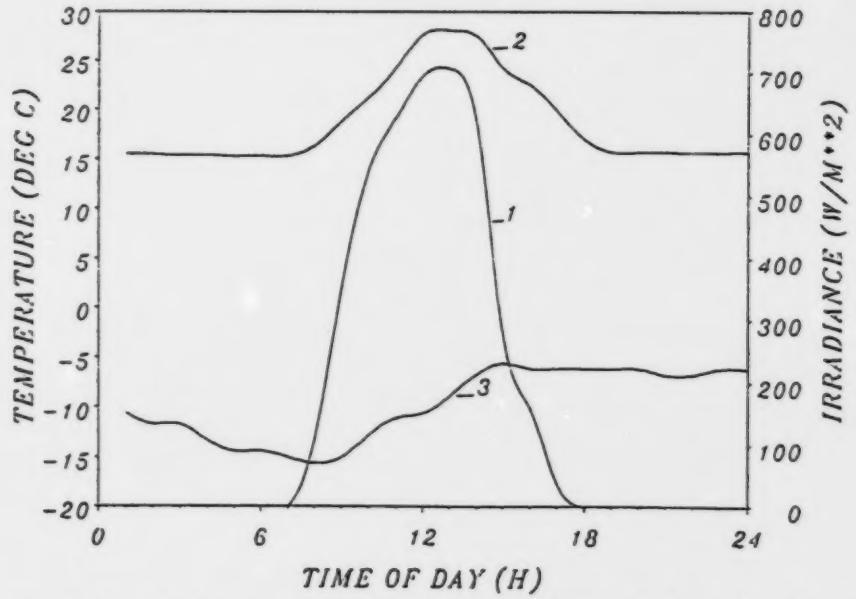


Figure 5. Reference conditions for winter. Nomenclature is the same as that of Figure 4.

$$PF = (T_{e\ ven} - T_{e\ reg}) / (T_{lim} - T_{e\ reg}) \qquad (38)$$

and within the comfort zone, $18.3^{o}C \leq T_{e\ reg} \leq 24.5^{o}C$, it is:

$$PF = 0 \qquad (39)$$

The theoretical results for optimum louver angles, auxiliary energy requirements and the performance factor in summer and winter are presented in Figures 6 to 8.

6. EXPERIMENTAL STUDY

An experimental study has been carried out in the solar laboratory for several days and for various louver angles. The experimental set-up is a closed box with an opening to install the test windows; it is 0.61 by 0.67 by 0.64 m high box fabricated of plywood (0.02 m thick plywood inside and 0.01 m thick plywood outside) and insulated with a 0.05 m styrofoam insulating material; it has a 0.30 by 0.47 m high opening and a hermetic door installed on opposite sides; it has an exposed heat transfer area of $A_T = 1.17\ m^2$; the overall heat transfer coefficient of the box walls is calculated as $U = 0.64\ W/m^2C$. The test apparatus is instrumented as shown in Figure 9: the temperatures inside and outside of the box and those on the inside and outside glass surfaces and the temperatures of the louver surface are measured using Copper - Constantan thermocouples; the total radiation on the horizontal surface and its beam component are measured using a pyranometer and a pyrheliometer (both Eppley). A data acquisition system (Philips Micom and Omega) is used to collect data. The experimental error in radiation measurements was estimated as $\pm$ 2.1 % of which $\pm$ 0.1

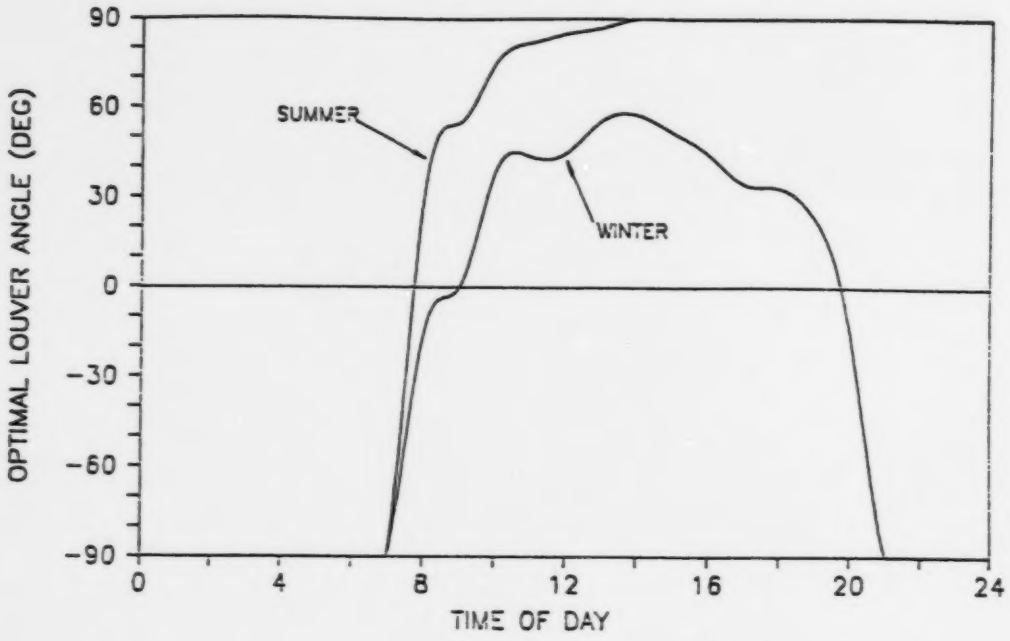


Figure 6. Optimum louver angle as a function of time in summer and winter periods.

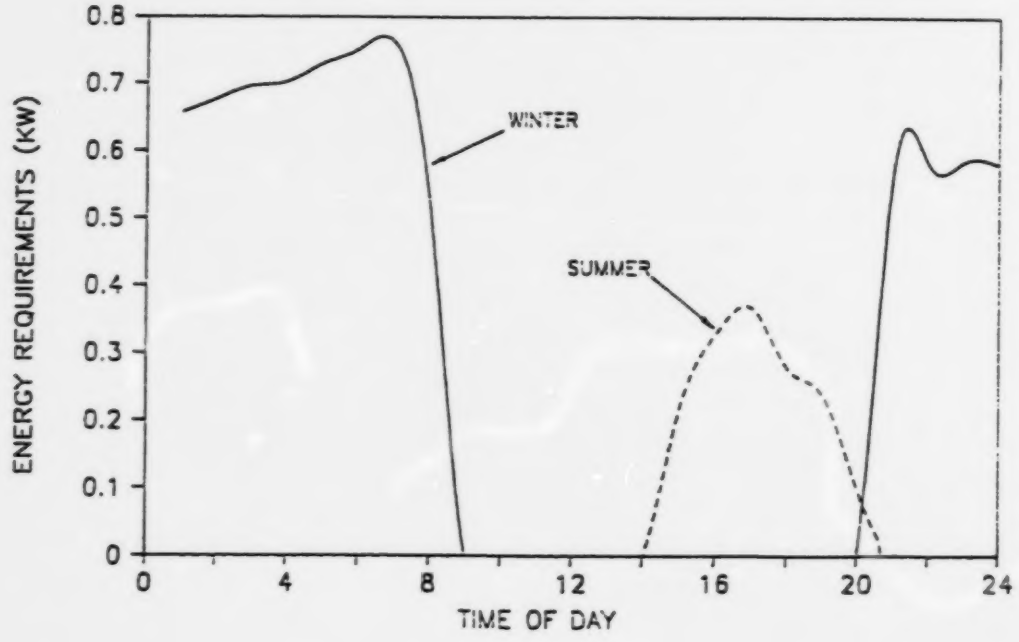


Figure 7. Auxiliary energy requirements as a function of time in summer and winter periods.

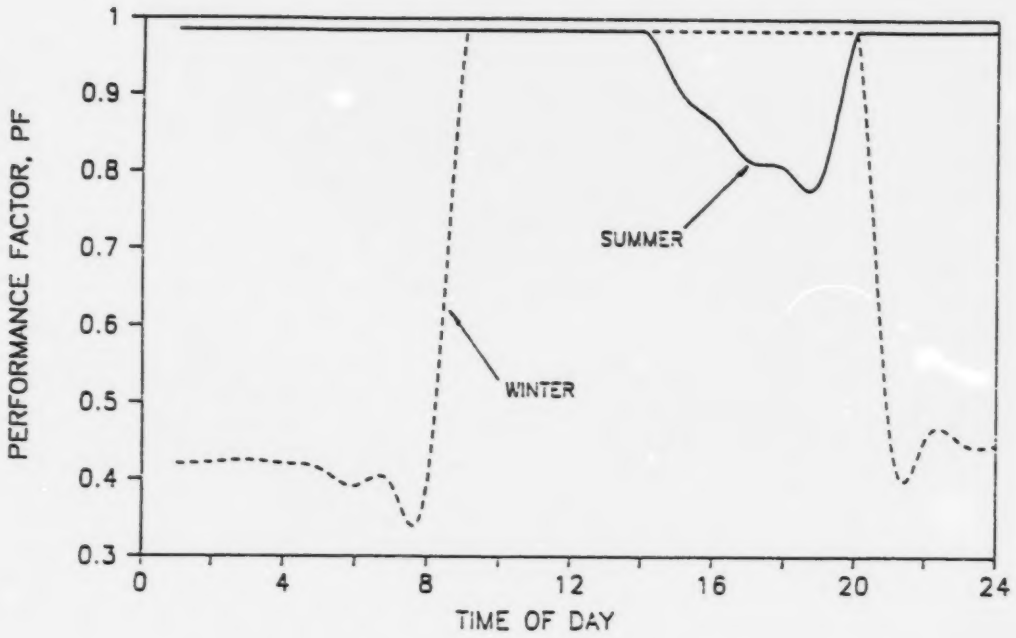


Figure 8. The hourly performance factor as a function of time for both seasons.

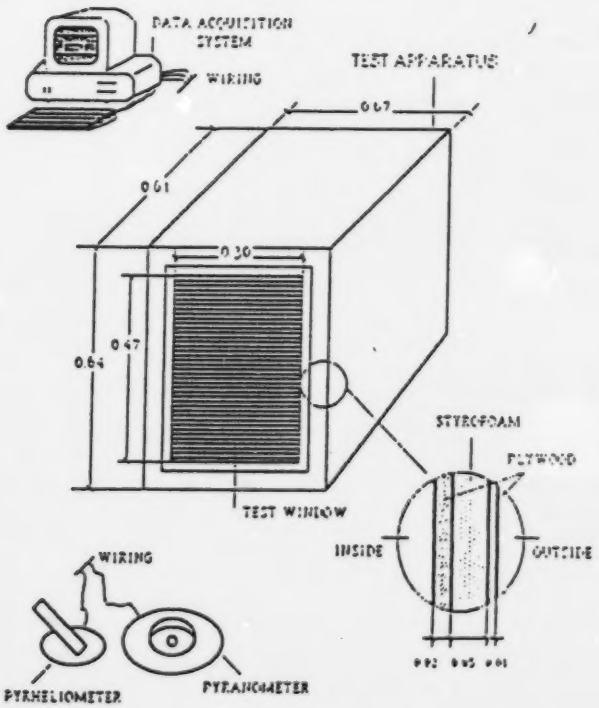


Figure 9. Schematic of the test apparatus and instrumentation.

% is due to the data collecting system; the experimental error in temperature measurements was estimated as ± 1 C which is the sum of ± 0.5 C due to thermocouples, ± 0.4 C due to radiation effects and ± 0.1 C due to the data acquisition system. From the solar radiation measurements, the diffuse component of the radiation, I_d is calculated and then I_b, I_d and T_a were used as input for a numerical simulation and T_7, T_{10}, T_e and the transmitted radiation were calculated and compared to experimental values. The system thermal resistance and the shading coefficient could also be calculated as discussed earlier (see Eqs. 34 to 36).

Experimental studies were carried out using 0.30 by 0.47 m high prototype windows manufactured using identical material and technique but with various additional features: i) reference window with louvers - both glass panes were clear 6 mm thick; ii) identical window with inside glass pane heat absorbing; iii) identical window with surface 9 of Figure 1 coated with low emissivity material. The optical and physical characteristics of the glass panes are shown in Table 2. The tempered ordinary glass panes are normally used in the manufacture of Vision Control windows which are supplied by Bouchard Glass Inc.; the low emissivity coated glass and heat absorbing glass are from Ford Glass Co., Montreal and their characteristics are from the Company's catalogues and from the literature [10,18].

Table 2. Optical and physical characteristics of the glass panes used.

GLASS	K (m^{-1})	e (mm)	ϵ
Common Glass	16.1	6	0.88
Low ϵ	16.1	6	0.20
Heat Absorbing	110.0	6	0.88

The experimental results are presented in Figures 10 to 19: the climatic conditions of the test days are shown in Figures 10 and 11; the total radiation incident on the window surface in Fig. 10 and the outside air temperature in Fig. 11; the experimental and theoretical floating air temperatures in the box are shown in Figures 12 to 14 for each type of window from Table 2 and for β = 0 and 90 deg. louver angles; the experimental and theoretical temperatures of the glass panes for the three cases and two louver angles are shown in Figures 15 to 17; finally the calculated thermal resistance and the shading coefficient of each type for two louver angles are shown in Figures 18 and 19.

7. RESULTS AND DISCUSSION

Thermal and Optical Performance: The comparison of the experimental and theoretical results in Fig. 12 to 17 indicate the goodness of the thermal model: the floating box air temperatures for three types of window and two louver angles are predicted within ± 6.0 % using the experimental data (see Figs. 12 to 14); the temperatures of the inside and outside glass panes are similarly predicted using the experimental data within ± 6.2 % (see Figs. 15 to 17). There-

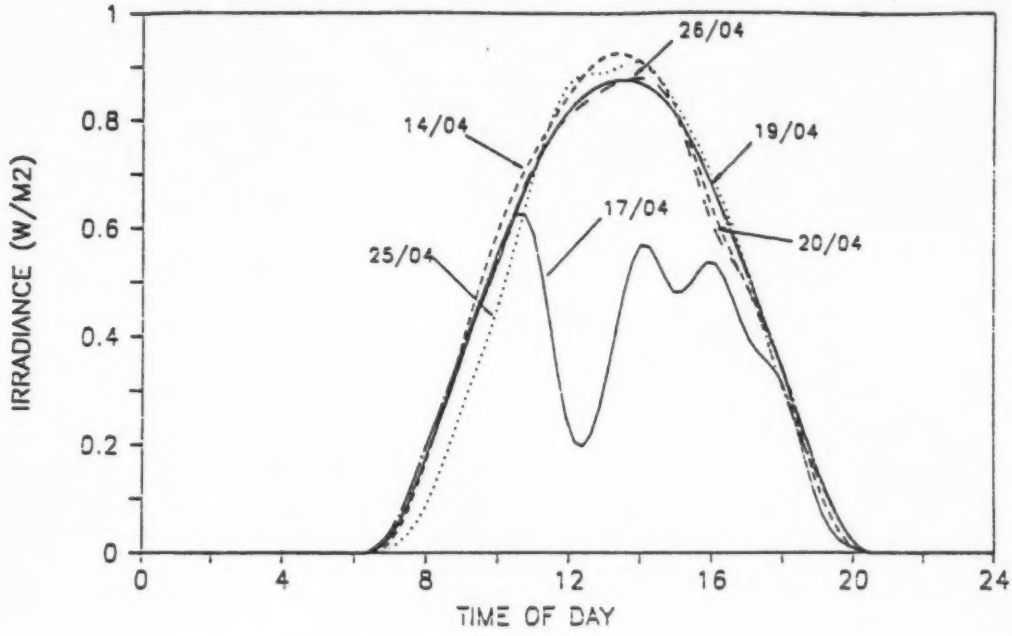


Figure 10. The total solar radiation on the surface of the window system for the test days.

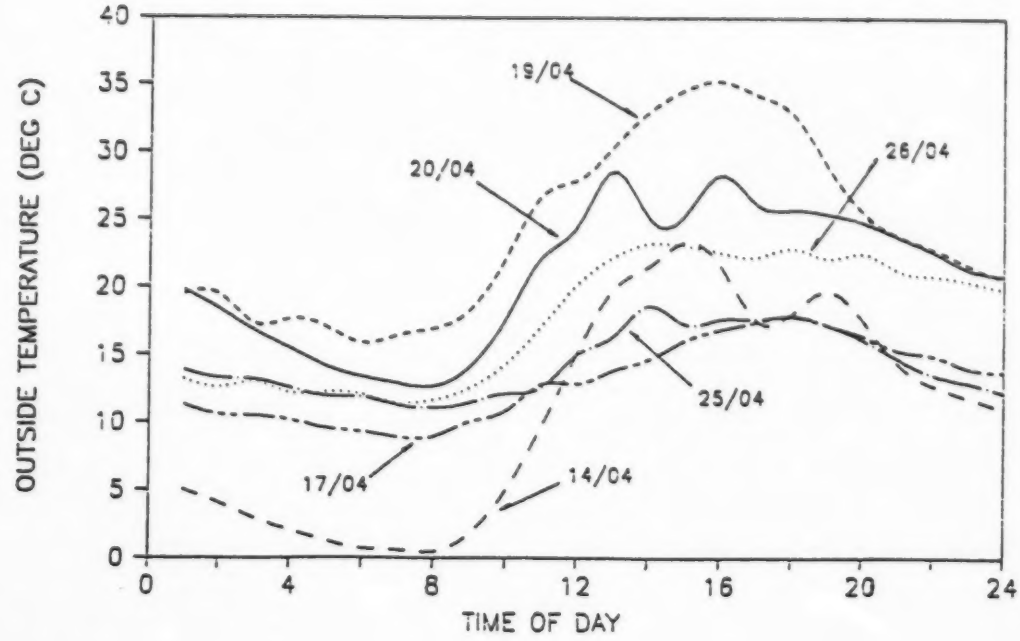


Figure 11. The outside air temperature for the test days.

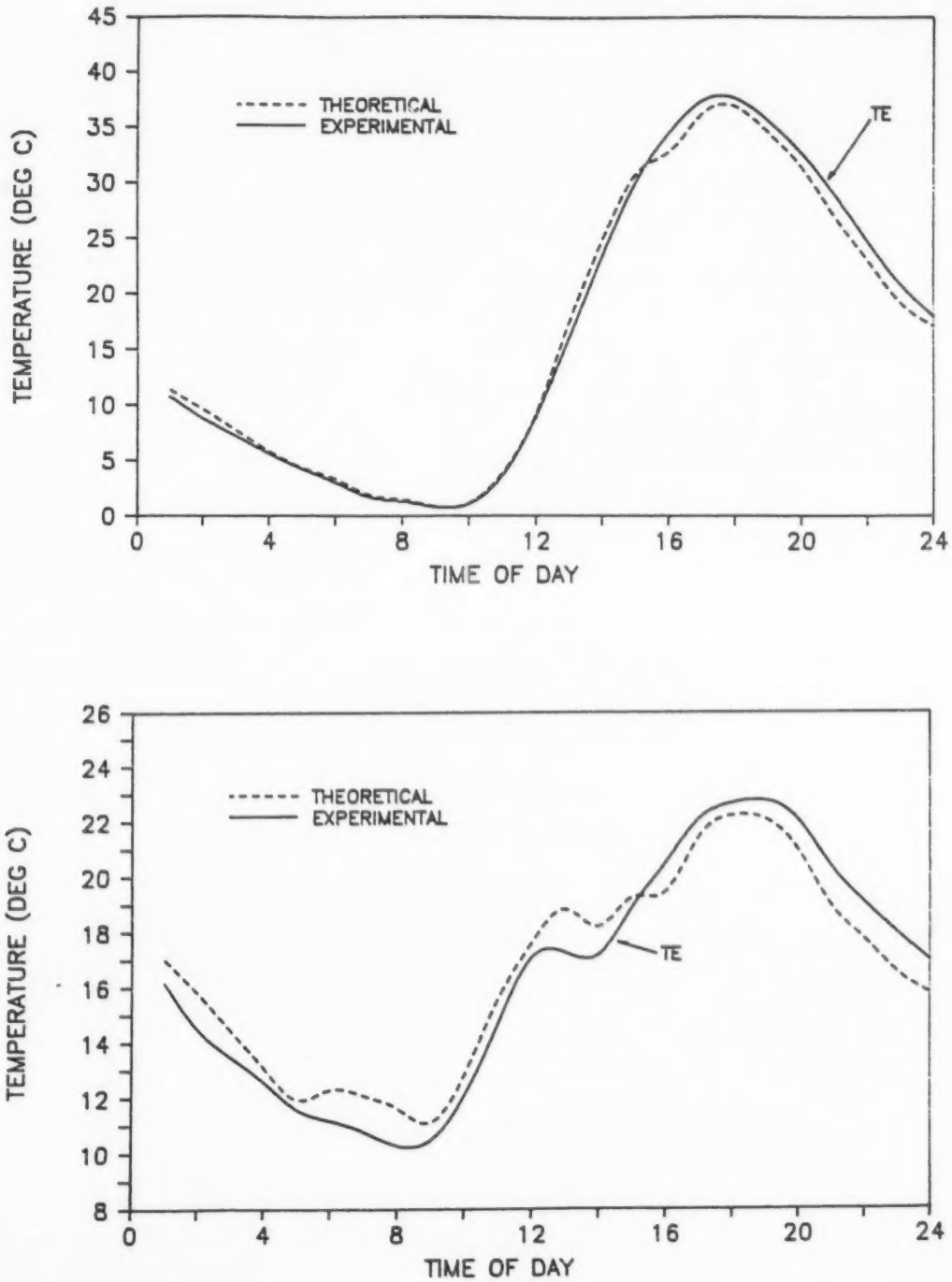
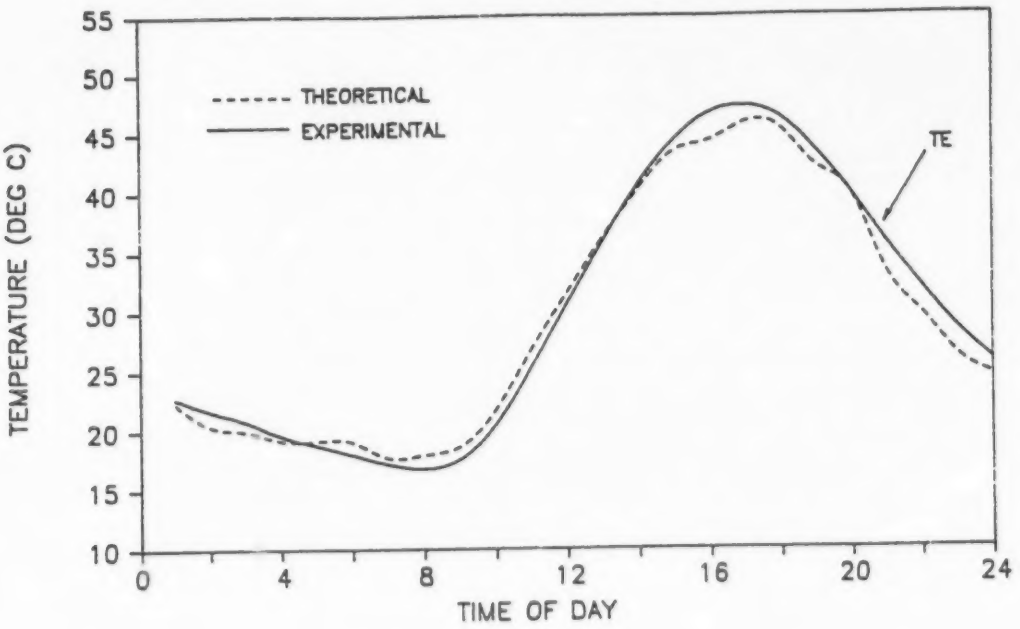


Figure 12. The experimental and theoretical floating box temperatures for the reference window: a) louver angle β = 0 (April 14) and b) β = 90 deg. (April 17).



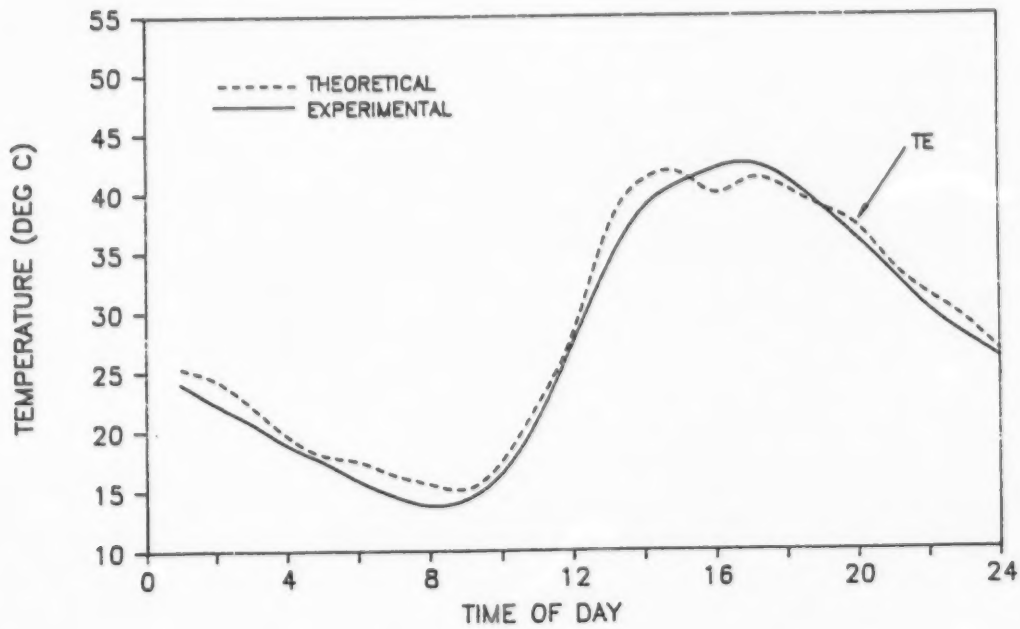


Figure 13. The experimental and theoretical floating box temperatures for the window with low ϵ coating: a) louver angle β = 0 (April 19) and b) β = 90 deg. (April 20).

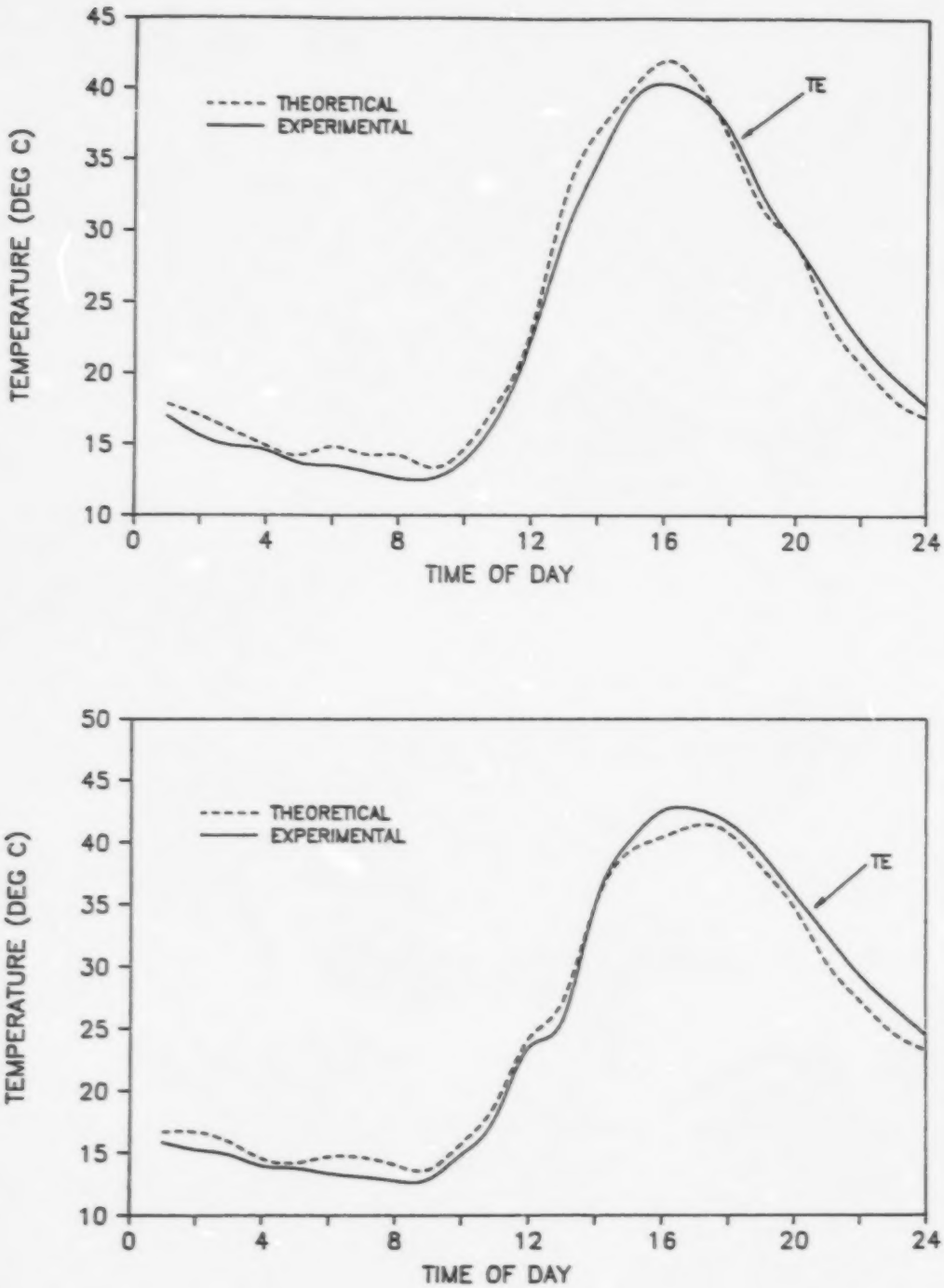


Figure 14. The experimental and theoretical floating box temperatures for the window with heat absorbing glass: a) louver angle β = 0 (April 25) and b) β = 90 deg. (April 26).

fore, in view of the comparison of the theoretical results of Table 2 with those of the literature and of the comparisons in Figs. 12 to 17, it is concluded that the accuracy of the thermal model is acceptable to study the thermal and optical characteristics of the Vision Control system and that it can be used as a design tool in system improvement studies.

The thermal resistance of the three types of window is obtained by averaging the values shown in Fig. 18; it is 0.33 m^2C/W for the reference window system with clear glass panes and louvers, 0.52 (β = 0) and 0.57 (β = 90) for the window with low ϵ and 0.33 for the window with heat absorbing glass. It can be seen that the thermal characteristics of the window with low ϵ are improved by about 58% (louvers open) to 73 % (louvers closed) over those of the reference system and that the thermal resistance characteristics of the window with heat absorbing glass are not changed. The optical characteristics of the windows in terms of shading coefficient are obtained by averaging the values obtained during sunshine hours of Fig. 19; the shading coefficient is 0.60 for the reference system, 0.60 for the window with low ϵ and 0.24 for the window with heat absorbing glass. Compared to the theoretical results of Table 1 the first two values are higher by about 7 (winter) to 11 % (summer) and the last is the same (winter) or lower by about 7% (summer). It can be seen that in addition to the control with louvers, the heat absorbing glass will improve the optical characteristics of the window by about 60 % over the reference system.

Optimum Louver Angle and Automatic Control: the hourly results indicated that in summer, the floating room temperature is lowest when the louvers are closed ($\beta = \pm 90^{o}$) and that depending on the hour of the day, hence the solar altitude, there is a floating room temperature for a specific louver angle which

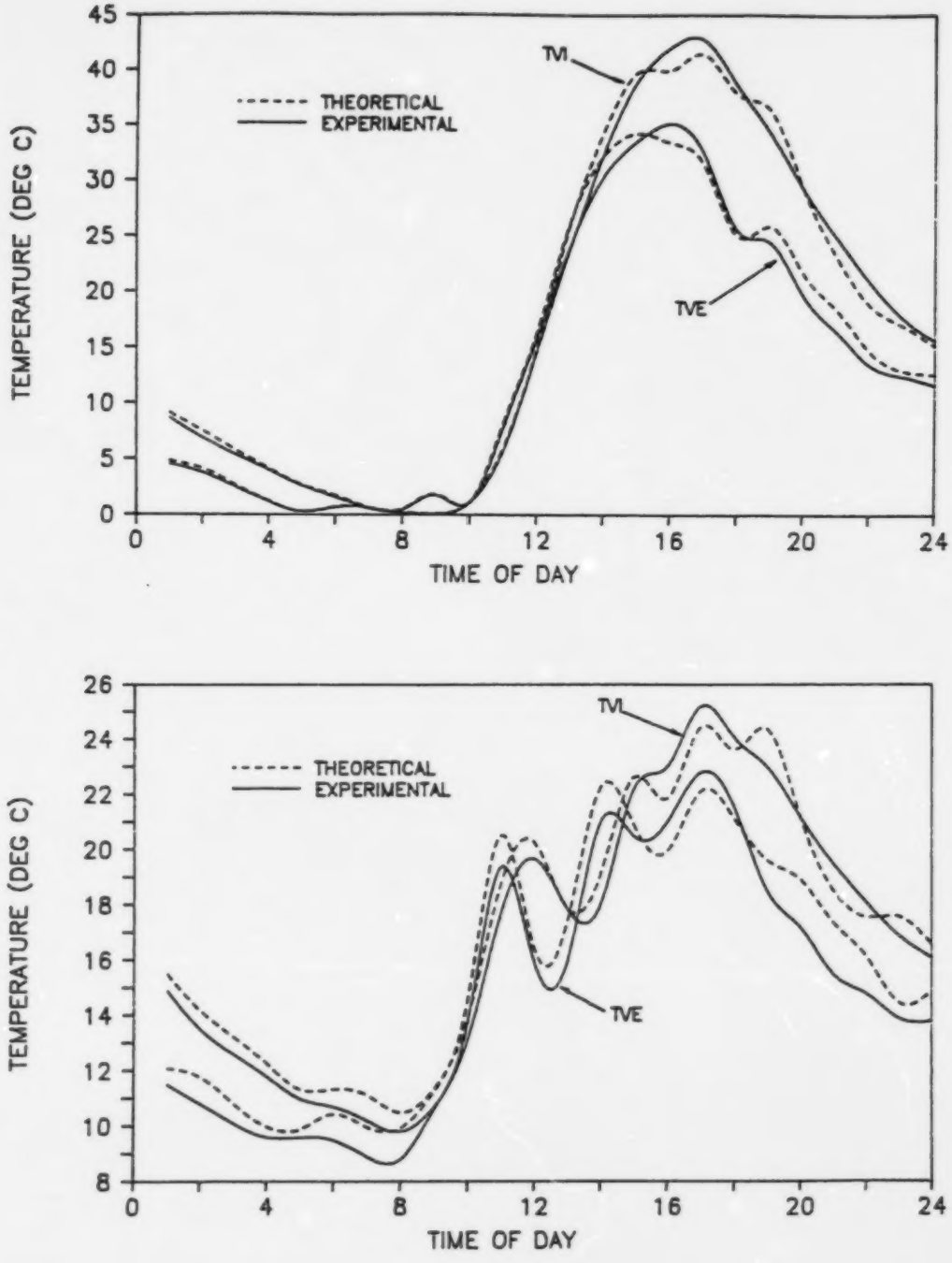


Figure 15. The experimental and theoretical inside and outside glass pane temperatures for the reference window: a) louver angle β = 0 (April 14) and b) β = 90 deg. (April 17).

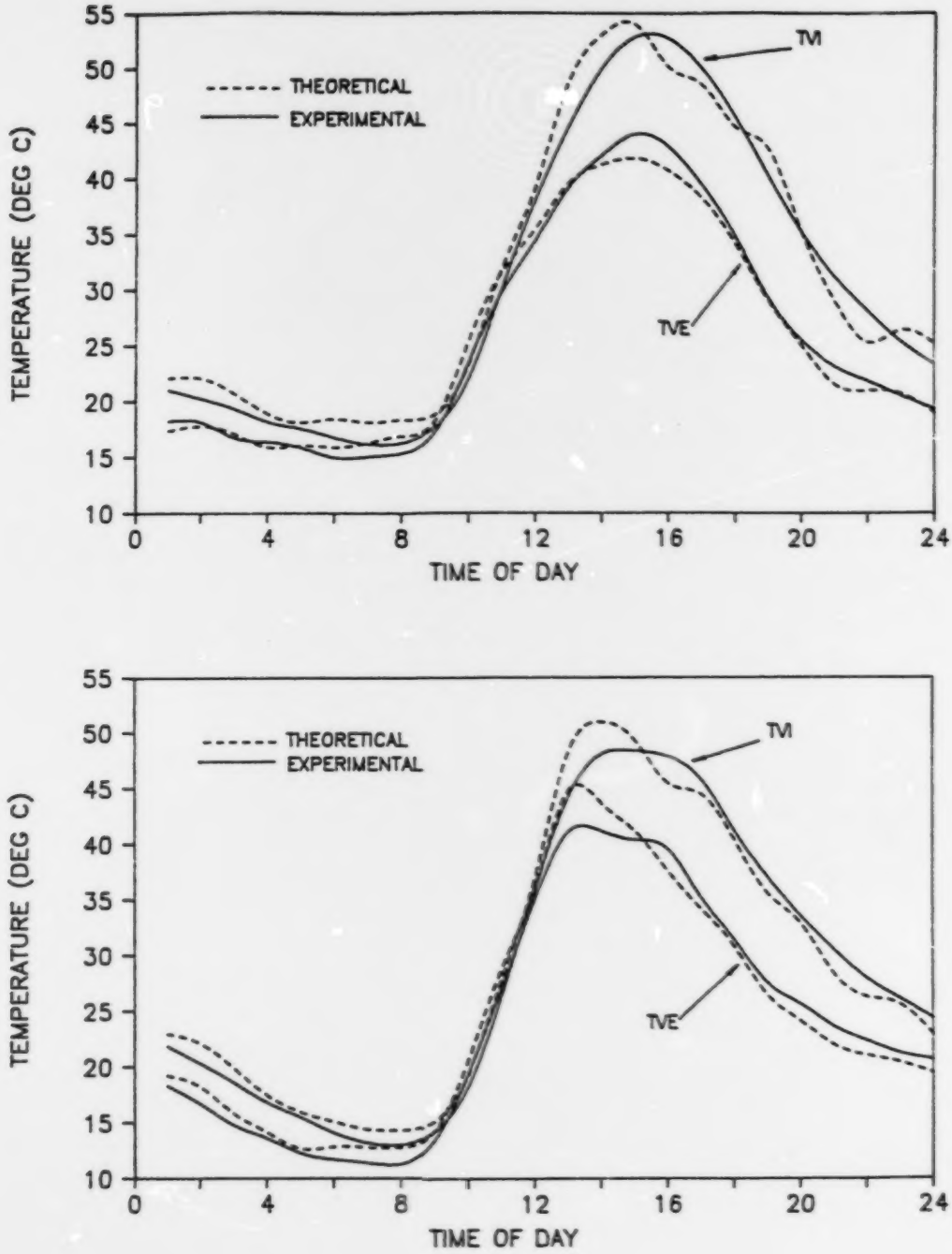


Figure 16. The experimental and theoretical inside and outside glass pane temperatures for the window with low ϵ coating: a) louver angle β = 0 (April 19) and b) β = 90 deg. (April 20).

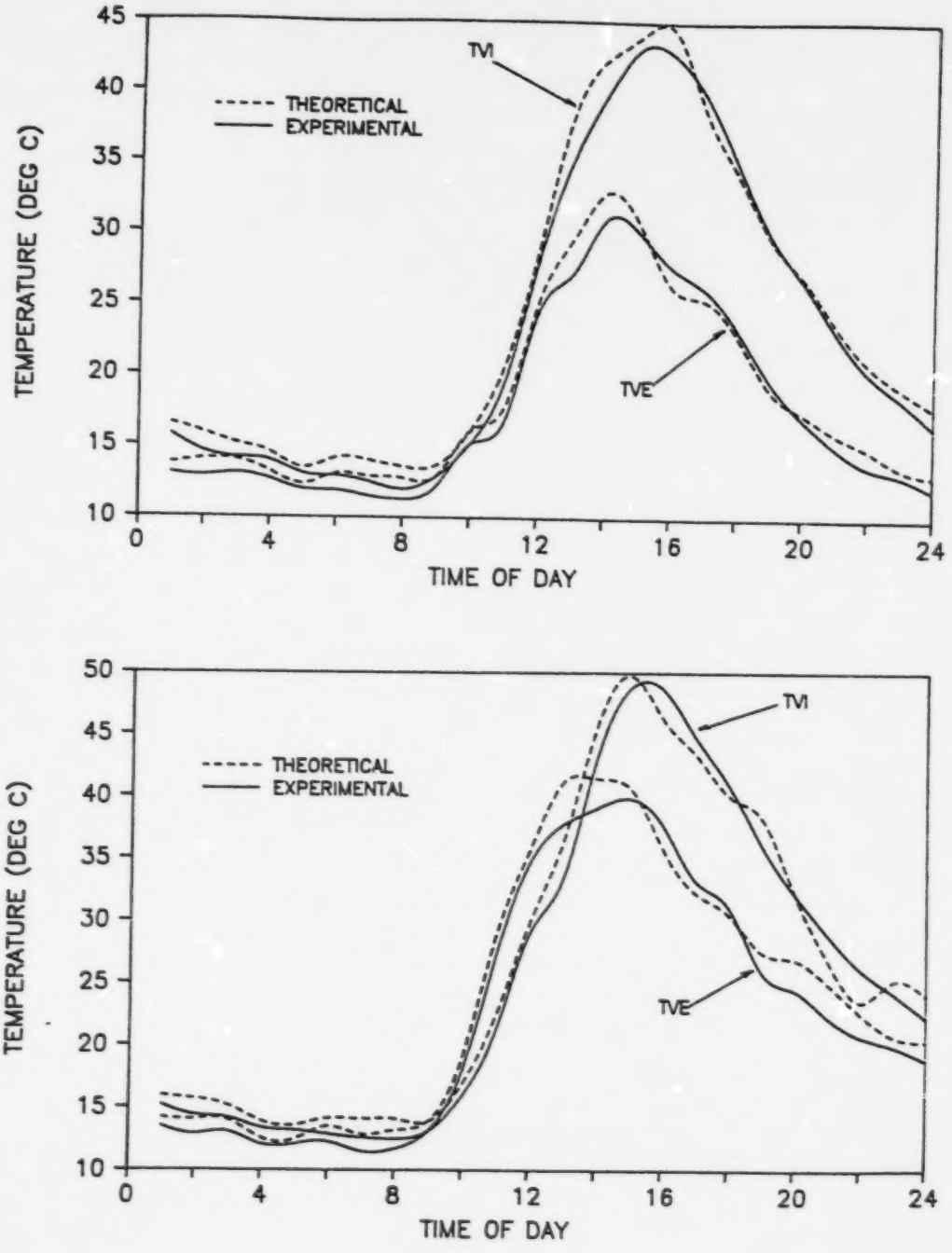


Figure 17. The experimental and theoretical inside and outside glass pane temperatures for the window with heat absorbing glass: a) louver angle β = 0 (April 25) and b) β = 90 deg. (April 26).

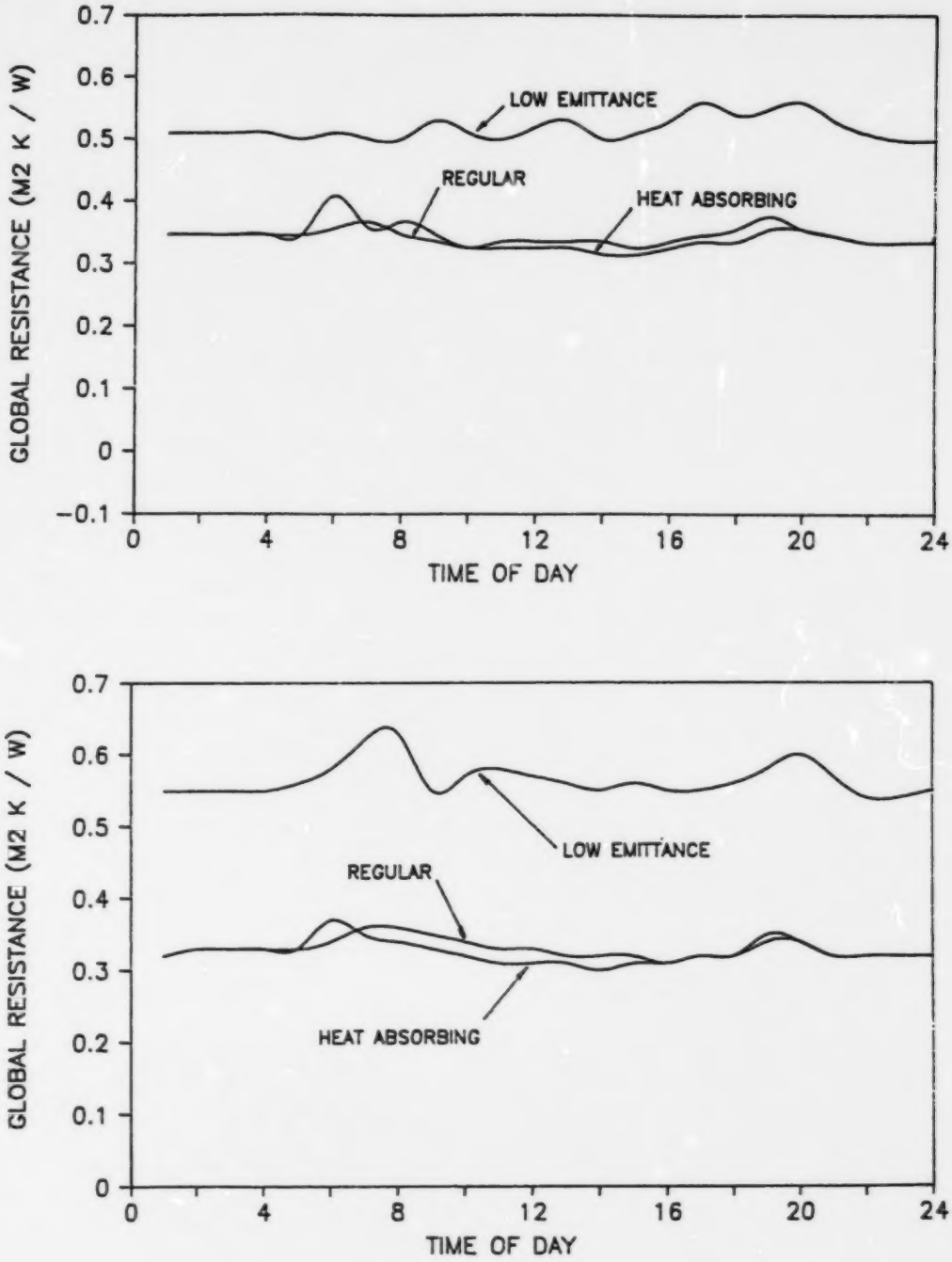


Figure 18. The thermal resistance of the three types of window as calculated from the experimental data using the thermal model: a) louver angle β = 0 and β = 90 deg.

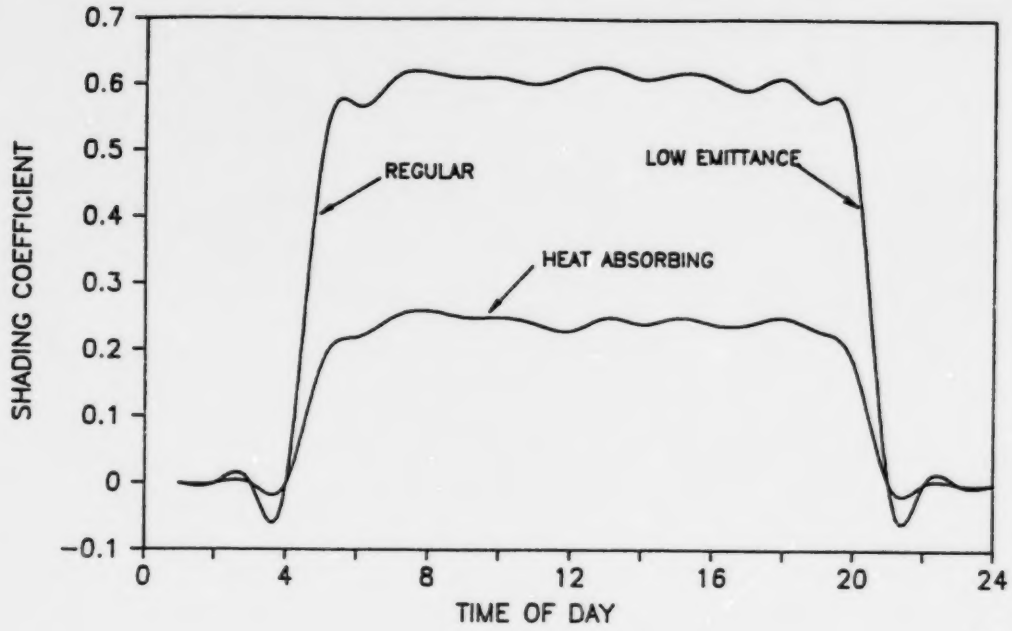


Figure 19. The shading coefficient of the three types of window as calculated from the experimental data using the thermal model: louver angle $\beta = 0$.

requires a minimum auxiliary energy. The hourly optimum louver angle is obtained if the floating room temperature is at the upper limit or closest to 24.5°C of the comfort zone. Similar hourly results were obtained for the winter day where the hourly optimum louver angle is obtained if the floating room temperature is at the lower limit or closest to 18.3°C of the comfort zone.

The hourly optimum louver angles and the auxiliary energy requirements associated with those hourly optimum angles at which the floating room temperature was outside of the comfort zone limits are presented in Figs. 6 and 7 for the summer and the winter days respectively. It is seen in Fig. 6 that during the summer day, the louvers are completely closed until 7:00 h. then following the sun's incidence angle as well as the intensity of the solar radiation, the louvers are positioned to reduce the transmission of beam radiation into the room.

i.e. $\beta > 0$ corresponding to blocking the view of the sun (see Fig. 1). It can also be seen that an auxiliary cooling energy is required in the afternoon although the louvers are completely closed from about 14:00 until 21:00 h. after which the radiation is zero and the outside temperature is lower than the upper limit of 24.5°C. Fig. 7 shows for the winter day that the louvers must be closed during the night period with a considerable heating energy and that they can be set to an optimum angle during day hours to receive the maximum solar radiation; it is seen that the auxiliary heating energy is zero from 9:00 to 20:00 h. which follows from the solar radiation data of Fig. 5

The hourly performance factor, PF, for both summer and winter days is shown in Fig. 8; it can be seen that during summer, PF equals 1 most of the time, except from 14:00 to 20:00 h. where it is slightly reduced to 0.8. With reference to Eq. 26, PF = 1 indicates an energy economy of 100% with an automated venetian blind window system in comparison to a similar ordinary window system. During winter, PF equal 1 from 9:00 to 20:00 h. and about 0.5 the rest of the time. Therefore, the energy economy is highest during day hours with an optimum solar energy reception and it is considerable at other times with increased thermal resistance of the system with the louvers closed.

Cost and Economical Considerations: It is quite complex to determine the energy economy and cost in general terms. However, by using the results of the example study of London, Ontario, an attempt can be made. The seasonal energy requirements of the building with a base window (without louvers) are determined to be 2.276 GJ/year for heating (without air conditioning, i.e. the energy is vented in over heated periods) and 1.105 GJ/year for air conditioning during summer. Based on the typical results, the annual energy economy with the improved Vision Control window is determined to be 1.2 GJ/year. The cost of the 2.58 m^2 window

with and without louvers is about 400$ and 235$ respectively, i.e. the additional investment is 165$. Assuming a 10 $/GJ energy cost, the simple payback period will be 165/12 = 13.75 years; the payback period for 5% fuel price escalation rate and 0% discount rate is about 10 years. The economical situation will be more favorable for applications in office buildings since they are usually air conditioned also in heating season to prevent any over heating.

8. CONCLUSIONS

In view of the results presented in the previous sections, following conclusions can be summarized:

i. The experimental verification has shown that the numerical model developed predicts satisfactorily the thermal performance of automated venetian blind window systems;

ii. The results of the theoretical and experimental studies indicate that the thermal resistance of the system can be increased by about 58 to 73 % using low ϵ glass; the optical performance in terms of shading coefficient can be decreased by about 60 % using heat absorbing glass.

iii. It is possible to control the louver position instantaneously at an optimum angle and the auxiliary energy requirements can be reduced to a minimum; the outside view can be provided as required with a minimum detriment to the energy economy by adjusting the louvers at near optimum angles, however by blocking the direct view of the sun;

9. RECOMMENDATIONS

It is recommended that

1. the findings for the thermal and optical improvements of the Vision Control system be implemented in full size systems;

2. in order to adjust the louver angles at optimum values and promote an energy conservation in various applications with Vision Control windows, an automatic control device be developed and marketed;

3. in order to promote the use of these systems by designers and architects, a user oriented simplified design tool for marketing purposes be developed based on the results of this study.

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11. NOMENCLATURE

A	:	surface area of the room (m^2)
C_p	:	specific heat (J/kg K)
D	:	glass to glass distance (m)
d	:	distance between louver end and glass (m)
e	:	glass thickness (m)
E_k	:	irradiance of the surface k (W/m^2)
F_b	:	porosity of the system (-)
F_{12}	:	radiation shape factor between elements 1 and 2 (-)
Gr	:	Grashof number (-)
h	:	convective heat transfer coefficient (W/m^2K)
H	:	height of the window (m)
I	:	incident solar radiation (W)
L_k	:	length of an element k (m)
ℓ	:	characteristic length (m)
Nu	:	Nusselt number (-)
PF	:	performance factor (-)
Pr	:	Prandtl number (-)
Q	:	heat exchanges in the room (W)
R	:	thermal resistance (m^2 C/W)
Ra	:	Rayleigh number (-)
Re	:	Reynolds number (-)
R_k	:	radiosity of the surface k (W/m^2)
SC	:	shading coefficient (-)
$SHGF$	:	solar heat gain factor (W/m^2)
T	:	absolute temperature (K)
t	:	time (s)

U : heat loss coefficient for the walls or heat loss coefficient (W/m^2K)

V : wind speed (m/s)

Vol : room volume (m^3)

w : louver width in the z direction (m)

Greek letters

α : absorption coefficient (-)

β : louver angle with the zx plane (deg)

Δ : increment (-)

ϵ : emissivity (-)

θ : solar radiation incidence angle (deg)

ν : kinematic viscosity (m^2/s)

ρ : density (kg/m^3)

σ : Stefan Boltzmann constant (-)

τ : transmission coefficient (-)

Φ_k : absorbed energy flux at element k (W/m^2)

Ψ_k : flux at element k (W/m^2)

Subscripts

a : outside conditions

aux : auxiliary

b : beam

con : conduction

C : convection

DSA : standard double strength sheet glass

d : diffuse

dp : dew point

e : room

g : global

GR : ground

i : inside glass

j : index

k : number of the element

L : louver

lim : comfort zone

m : room walls

o : outside glass

r : reflected

R : infrared

reg : regular double glass window

RS : infrared and solar

S : solar

SKY : sky

T : total

top : window system

ven : venetian blind window system

Superscript:

t : time

CONTRACT DIRECTORY INFORMATION

TITLE: THERMAL IMPROVEMENT OF VISION CONTROL WINDOWS

CONTRACTOR: Unicel Inc., 88 de Vaudreuil, Boucherville , Quebec, J4B 5G4

SCIENTIFIC AUTHORITY: Tim Mayo, Solar Energy Development Program, Energy, Mines and Resources, 460 O'Connor St., 4th Floor, Ottawa, Ontario K1A 0E4

PRINCIPAL INVESTIGATOR: E. Bilgen, (514) 695-1363

DURATION: 10 July 1986 - 30 April 1987

COST: Total Contract Cost: $ 49,000; Contractor Contribution: $ 12,250

OBJECTIVES: The main objectives of this project were: 1. Improvement of thermal and optical characteristics of Vision Control windows fabricated by Unicel; 2. Thermal analysis (by radiation, convection and conduction) of the system to develop a design tool for improvement, modification and better utilization of materials.

RESULTS: 1. The following improvement areas were identified: a) use of low emittance glass; b) use of heat absorbing glass; c) use of low emittance coating of louvers; d) decreasing of the distance between the inside glass surfaces and the louver ends. The results indicated that a) and b) were the possible improvement areas; 2. Optimum louver angle study indicated that an automatic control strategy could result in considerable energy savings in winter and summer operations of these systems.

CONCLUSIONS: 1. The thermal model developed can be used as a design tool to identify the improvement areas of the system; 2. the thermal resistance of the system can be increased by 58 to 73 % using low emittance glass; 3. the optical performance of the system, i.e. shading coefficient can be improved by 60 % using heat absorbing glass; 4. using an automatic control device considerable energy economies can be realized.

RECOMMENDATIONS: It is recommended that 1. the findings for the thermal and optical improvements of the Vision Control system be implemented in full size systems; 2. in order to adjust the louver angles at optimum values, an automatic control device be developed; 3. a simplified design tool for marketing purposes be developed based on the results of this study.